Nano-engineered Casimir forces

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Collaborators

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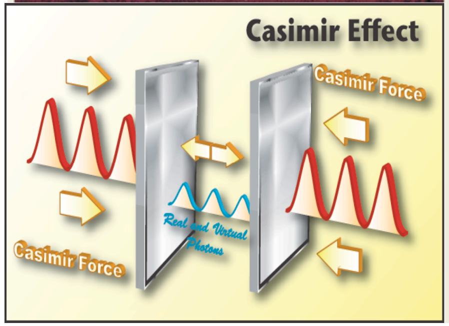
- Theory:

Engineering the Casimir force with metamaterials:	Peter Milonni (LANL) Felipe da Rosa (LANL)
Engineering the Casimir force with geometry:	Paulo Maia Neto (Rio) Serge Reynaud (Paris)

- Experiment:

Metamaterials for Casimir force:	Toni Taylor (LANL) Hou-Tong Chen (LANL)
Casimir force measurements:	Steve Lamoreaux (Yale) Ricardo Decca (Indiana) Roberto Onofrio (Dartmouth)

The Casimir force



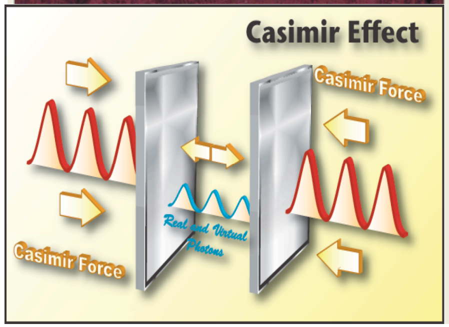
Casimir forces originate from changes in quantum vacuum fluctuations imposed by surface boundaries

They were predicted by the Dutch physicist Hendrik Casimir in 1948

Dominant interaction in the micron and sub-micron lengthscales

$$\boxed{\frac{F}{A} = \frac{\pi^2}{240}\frac{\hbar c}{d^4}} \qquad (130\mathrm{nN/cm^2} \ @\ d = 1\mu\mathrm{m})$$

The Casimir force



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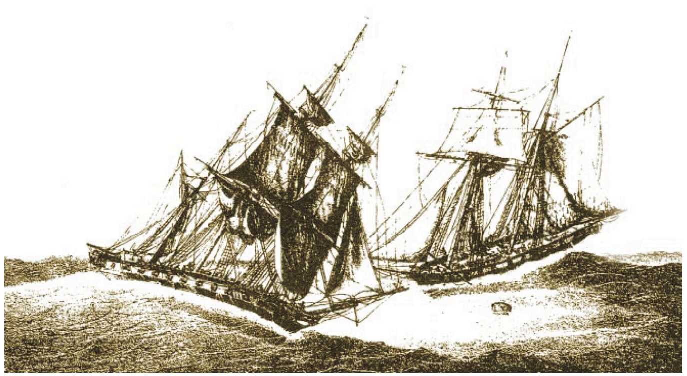
Classical Analog: L'Album du Marin (1836)



Relevant applications

- Gravitation / Particle theory:

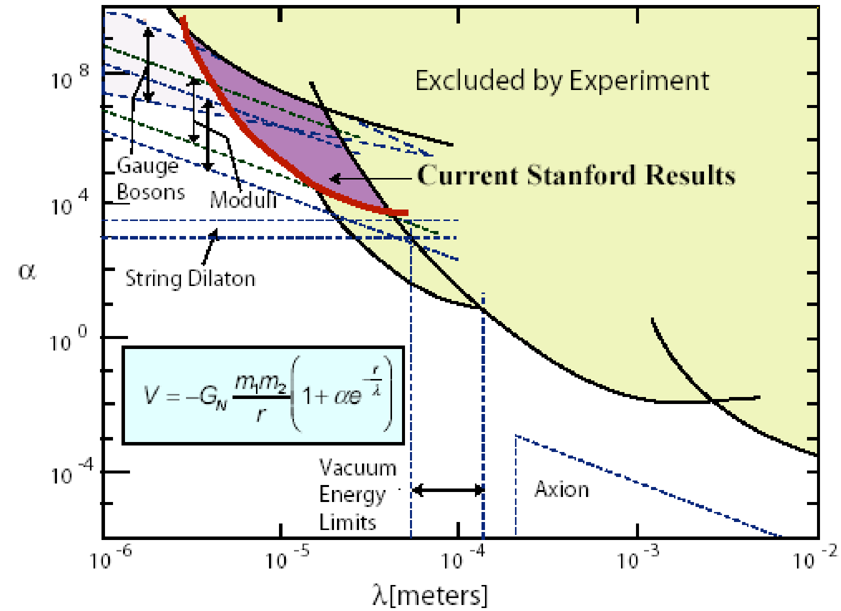
Some theories of particle physics predict deviations from the Newtonian gravitational potentials in the micron and submicron range

The Casimir force is the main background force to measure these non-Newtonian corrections to gravity

Yukawa-like potential:

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

Phase Space



2003 Rencontres de Moriond

S. J. Smullin, Stanford University

Relevant applications

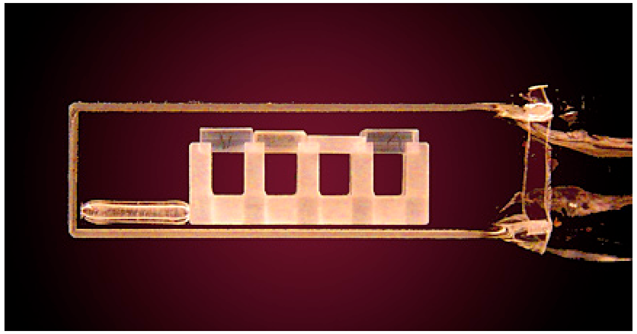
- Quantum Science and Technology:

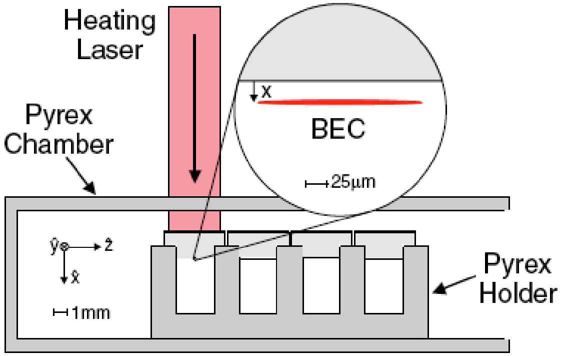
  Atom-surface interactions

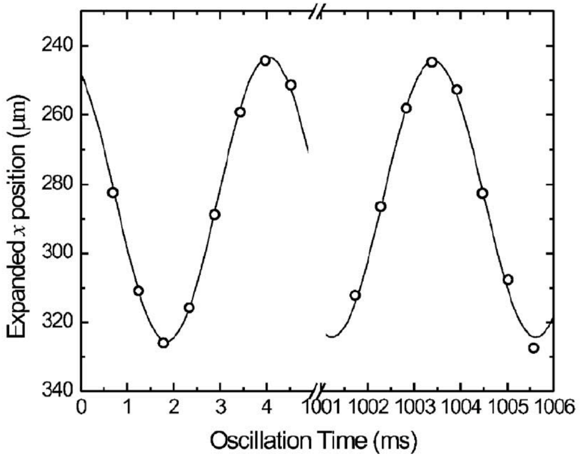
  Precision measurements

Example: Casimir-Polder interaction between a BEC and a surface

E. Cornell et al, Phys. Rev. Lett. 98, 063201 (2007)







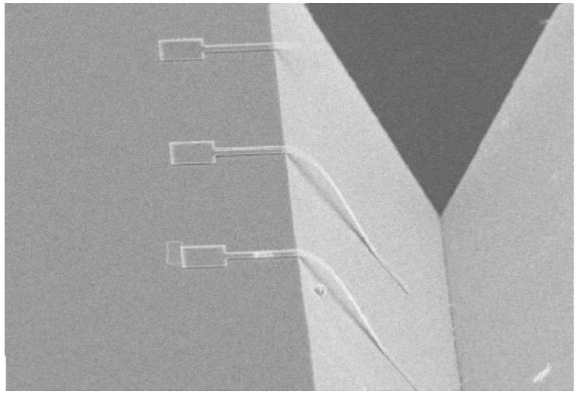
$$\gamma_x \equiv \frac{\omega_x - \omega_x'}{\omega_x} \simeq -\frac{1}{2\omega_x^2 m}\partial_x^2 U^*$$

Relevant applications

- Nanotechnology:

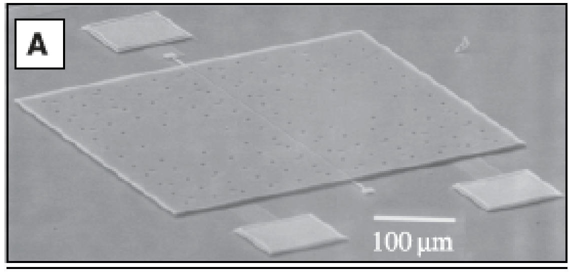
Problems with stiction of movable parts in MEMS

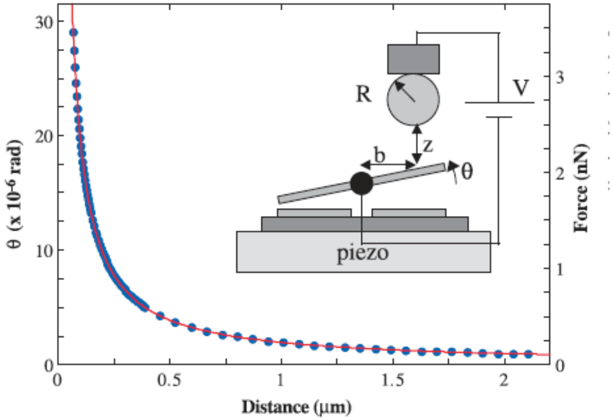
"pull-in" effect



Zhao et al, Adhesion Sci. Technol. 17, 519 (2003)

Actuation in NEMS and MEMS driven by Casimir forces

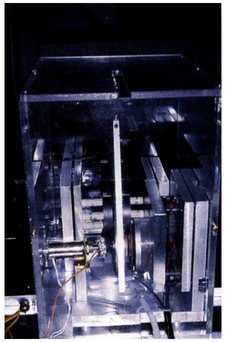
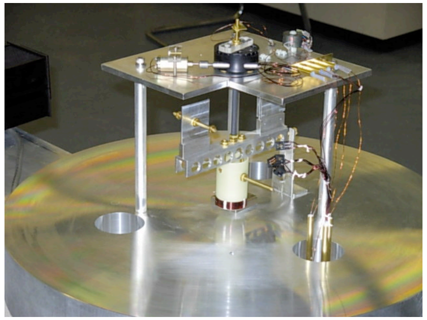




F. Capasso et al, Science 291, 1941 (2001)

Modern experiments

- Torsion pendulum

sphere-plane, d=1-10 um
Lamoreaux

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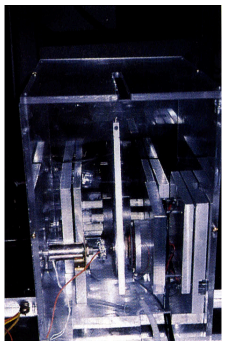
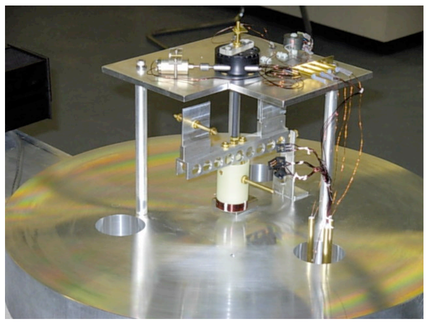
- Torsion pendulum





sphere-plane, d=1-10 um
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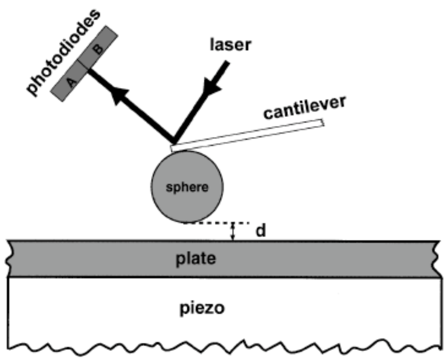
- Atomic force microscope



sphere-plane, d=200-1000 nm
Mohideen

Modern experiments

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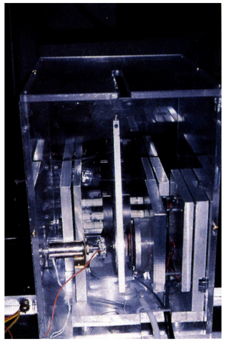
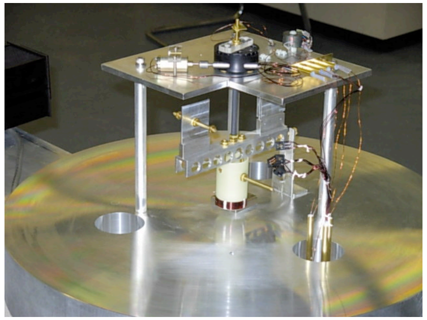
Torsion pendulum





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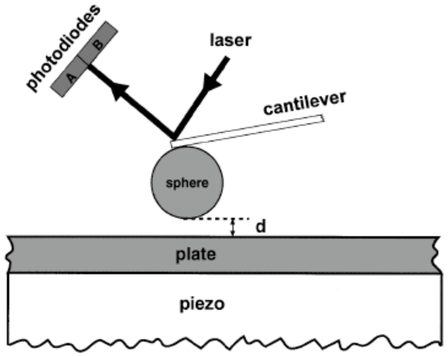

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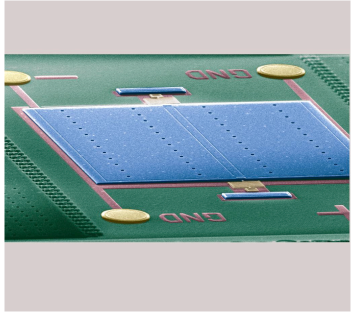
MEMS and NEMS



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Capasso, Decca

Modern experiments

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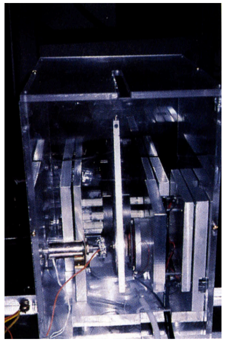

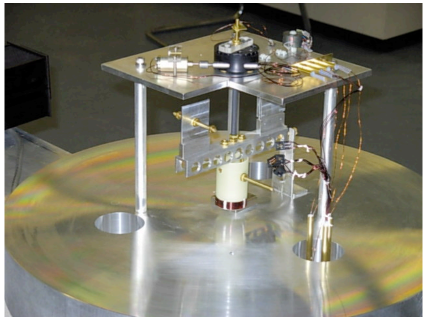

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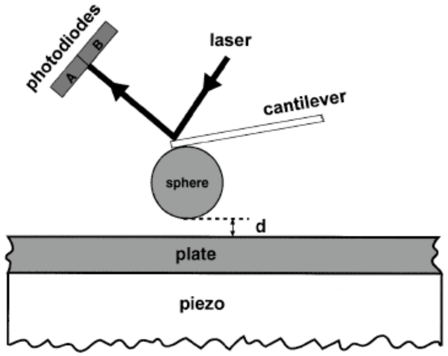

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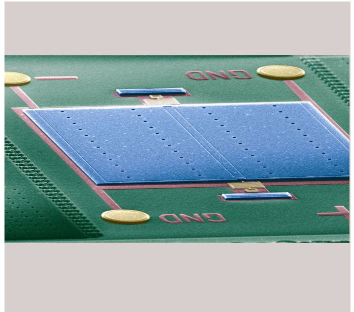

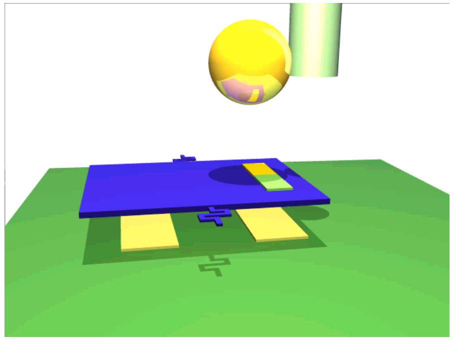

sphere-plane, d=200-1000 nm
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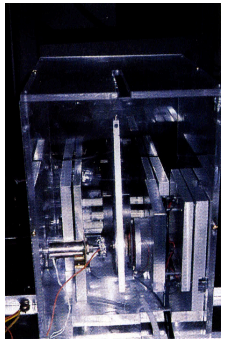

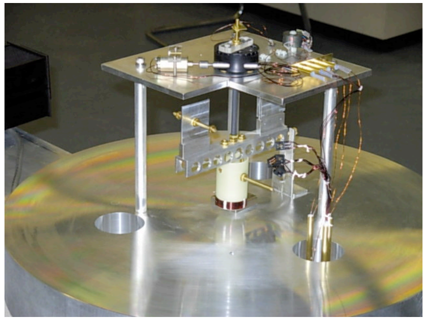

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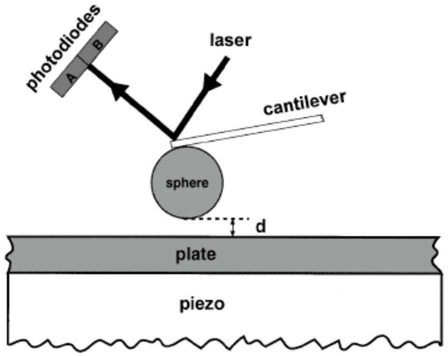

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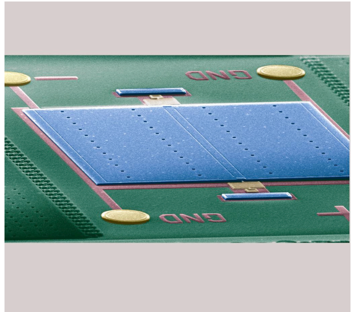
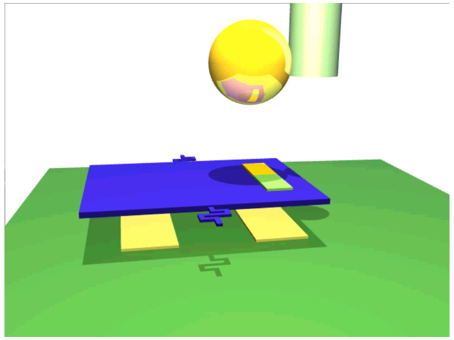
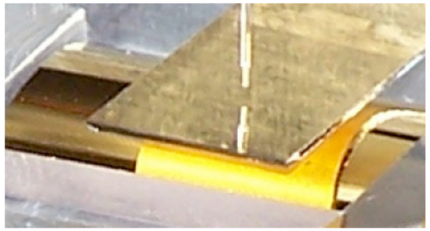




sphere-plane, d=200-1000 nm
Capasso, Decca

Micro-cantilever



plane-plane, cylinder-plane, d=1-3 um
Onofrio

Tailoring the Casimir force

The magnitude and sign of the Casimir force depend on the geometry and composition of surfaces

Engineer geometries and designer materials for various applications:

- Demonstration of strongly modified/repulsive Casimir forces
- Demonstration of vacuum drag via lateral Casimir forces

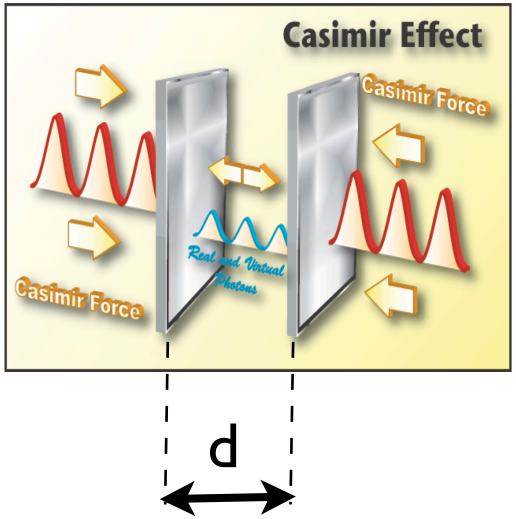
From ideal to real materials: The Lifshitz formula

$$\frac{F}{A} = \frac{\pi^2}{240}\frac{\hbar c}{d^4} \longrightarrow \frac{F}{A} = 2k_B T \sum_{n=0}^{\infty} \int_{\xi_n/c}^{\infty} \frac{d\kappa}{2\pi}\kappa^2 \sum_{\lambda=\mathrm{TE,TM}} \left(\frac{e^{2\kappa d}}{r_{\lambda_1} r_{\lambda_2}} - 1 \right)^{-1}$$

Dominant frequencies in the near-infrared/optical region of the EM spectrum (gaps d= 200-1000 nm)

The Lifshitz formula

$$\frac{F}{A} = 2k_B T \sum_{n=0}^{\infty} \int_{\xi_n/c}^{\infty} \frac{d\kappa}{2\pi} \kappa^2 \sum_{\lambda=\mathrm{TE,TM}} \left(\frac{e^{2\kappa d}}{r_{\lambda_1} r_{\lambda_2}} - 1 \right)^{-1}$$



$$\omega_n = i\xi_n = 2\pi i n k_B T/\hbar$$ Matsubara frequencies

$$r_{\mathrm{TM}} = \frac{\epsilon(i\xi_n)c\kappa - \sqrt{\xi_n^2[\epsilon(i\xi_n)\mu(i\xi_n) - 1] + \kappa^2 c^2}}{\epsilon(i\xi_n)c\kappa + \sqrt{\xi_n^2[\epsilon(i\xi_n)\mu(i\xi_n) - 1] + \kappa^2 c^2}}$$

Reflection coefficients

$$r_{\mathrm{TE}} = r_{\mathrm{TM}} \text{ with } \epsilon \leftrightarrow \mu$$

Kramers-Kronig (causality) relations:

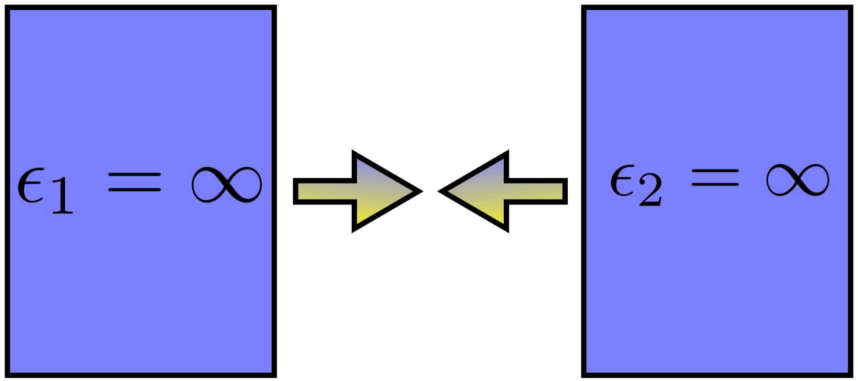
$$\epsilon(i\xi_n) = 1 + \frac{2}{\pi} \int_0^{\infty} \frac{\omega \epsilon''(\omega)}{\omega^2 + \xi_n^2} d\omega \qquad \mu(i\xi_n) = 1 + \frac{2}{\pi} \int_0^{\infty} \frac{\omega \mu''(\omega)}{\omega^2 + \xi_n^2} d\omega$$

Casimir attraction-repulsion

- Ideal attractive limit

Casimir 1948

$$\boxed{\frac{F}{A} = +\frac{\pi^2}{240}\,\frac{\hbar c}{d^4}}$$



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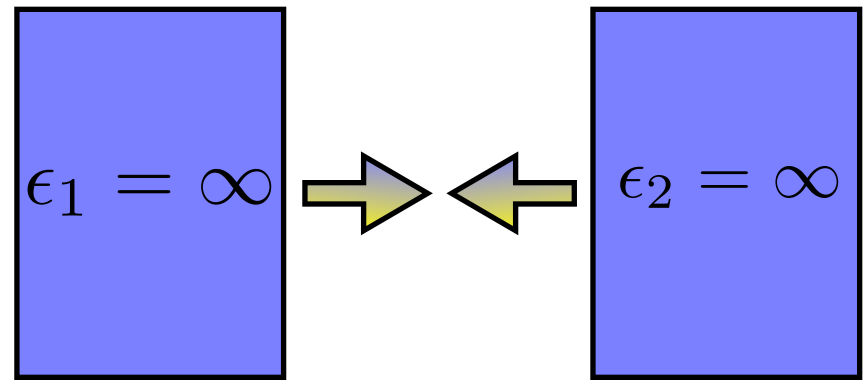
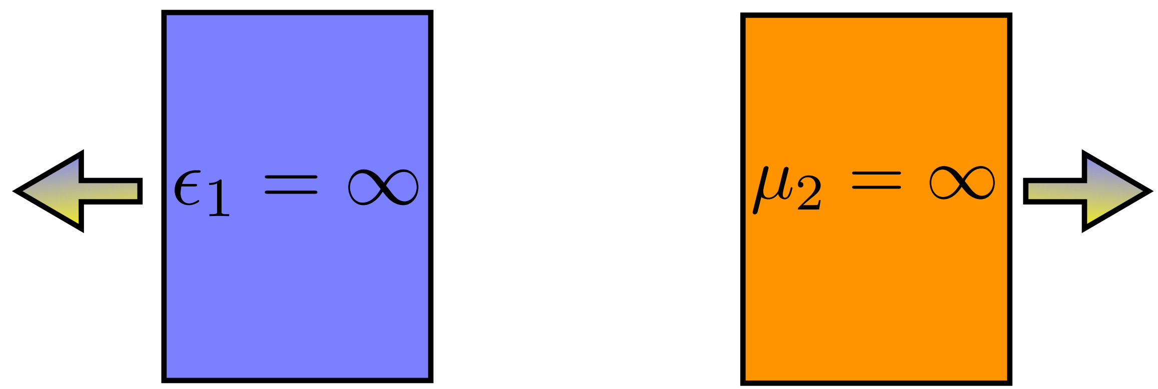


- Ideal repulsive limit

Boyer 1974

$$\boxed{\frac{F}{A} = -\frac{7}{8}\,\frac{\pi^2}{240}\,\frac{\hbar c}{d^4}}$$



Casimir attraction-repulsion

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- ## Ideal attractive limit

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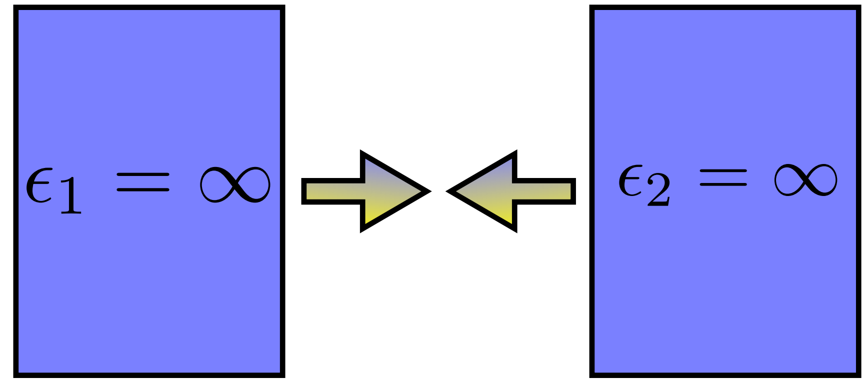

- ## Ideal repulsive limit

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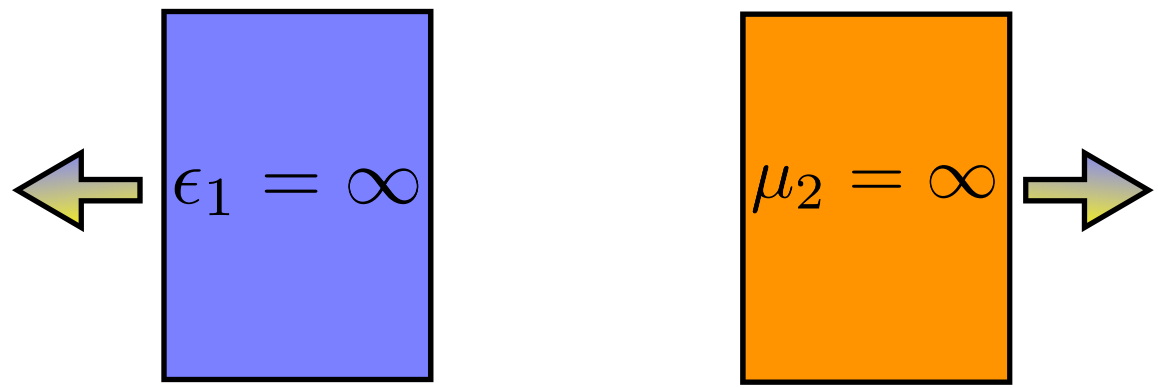

- ## Real repulsive limit

  Casimir repulsion is associated with strong electric-magnetic interactions. However, natural occurring materials do NOT have strong magnetic response in the optical region, i.e. $\mu = 1$

Casimir attraction-repulsion

- **Ideal attractive limit**

Casimir 1948

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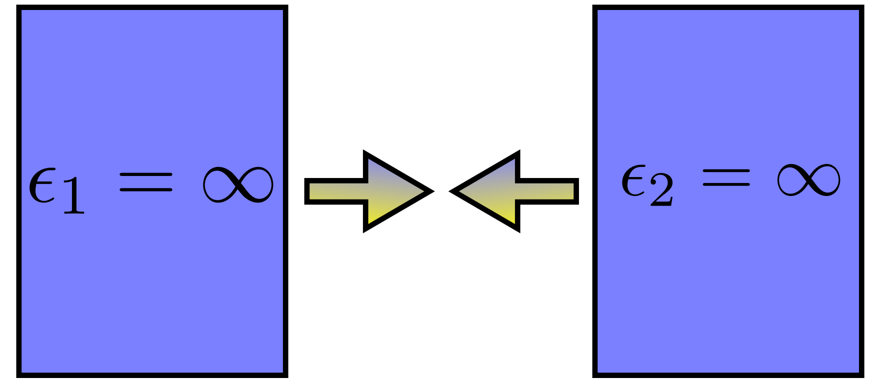
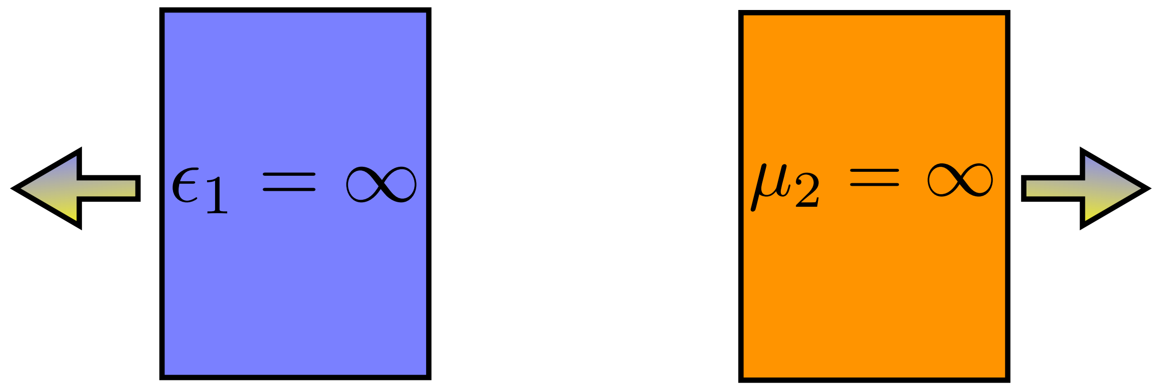


- **Ideal repulsive limit**

Boyer 1974

$$\boxed{\frac{F}{A} = -\frac{7}{8}\frac{\pi^2}{240}\frac{\hbar c}{d^4}}$$



- **Real repulsive limit**

Casimir repulsion is associated with strong electric-magnetic interactions. However, natural occurring materials do NOT have strong magnetic response in the optical region, i.e. $\mu = 1$ $\longrightarrow$ **Metamaterials**

Quantum levitation by LHM?

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Physicists have 'solved' mystery of levitation - Telegraph http://www.telegraph.co.uk/news/main.jhtml?xml=/news/2007/08/0...

Physicists have 'solved' mystery of levitation

By Roger Highfield, Science Editor
Last Updated: 1:41am BST 08/08/2007

Levitation has been elevated from being pure science fiction to science fact, according to a study reported today by physicists.

In earlier work the same team of theoretical physicists showed that invisibility cloaks are feasible.

Now, in another report that sounds like it comes out of the pages of a Harry Potter book, the University of St Andrews team has created an 'incredible levitation effects' by engineering the force of nature which normally causes objects to stick together.

Professor Ulf Leonhardt and Dr Thomas Philbin, from the University of St Andrews in Scotland, have worked out a way of reversing this phenomenon, known as the Casimir force, so that it repels instead of attracts.

Their discovery could ultimately lead to frictionless micro-machines with moving parts that levitate But they say that, in principle at least, the same effect could be used to levitate bigger objects too, even a person.

In theory the discovery could be used to levitate a person

The Casimir force is a consequence of quantum mechanics, the theory that describes the world of atoms and subatomic particles that is not only the most successful theory of physics but also the most baffling.

The force is due to neither electrical charge or gravity, for example, but the fluctuations in all-pervasive energy fields in the intervening empty space between the objects and is one reason atoms stick together, also explaining a "dry glue" effect that enables a gecko to walk across a ceiling.

Now, using a special lens of a kind that has already been built, Prof Ulf Leonhardt and Dr Thomas Philbin report in the New Journal of Physics they can engineer the Casimir force to repel, rather than attract.

Because the Casimir force causes problems for nanotechnologists, who are trying to build electrical circuits and tiny mechanical devices on silicon chips, among other things, the team believes the feat could initially be used to stop tiny objects from sticking to each other.

Prof Leonhardt explained, "The Casimir force is the ultimate cause of friction in the nano-world, in particular in some microelectromechanical systems.

Such systems already play an important role - for example tiny mechanical devices which triggers a car airbag to inflate or those which power tiny 'lab on chip' devices used for drugs testing or chemical analysis.

Micro or nano machines could run smoother and with less or no friction at all if one can manipulate the force." Though it is possible to levitate objects as big as humans, scientists are a long way off developing the technology for such feats, said Dr Philbin.

The practicalities of designing the lens to do this are daunting but not impossible and levitation "could happen over quite a distance".

Prof Leonhardt leads one of four teams - three of them in Britain - to have put forward a theory in a peer-reviewed journal to achieve invisibility by making light waves flow around an object - just as a river flows undisturbed around a smooth rock.

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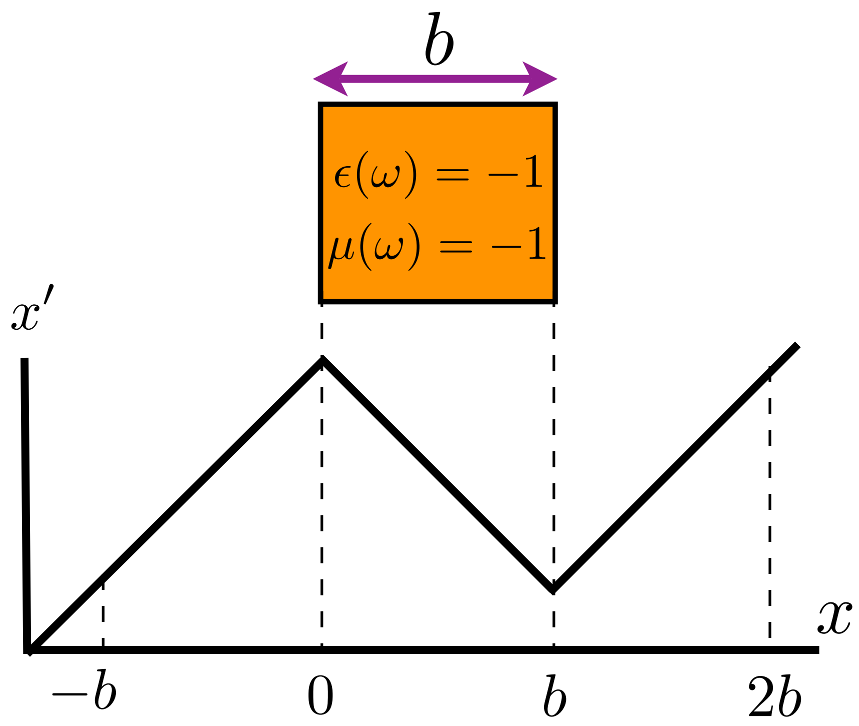
Quantum levitation by LHM?

Transformation media Leonhardt et al, NJP 9, 254 (2007)



Perfect lens: EM field in -b<x<0 is mapped into x'. There are two images, one inside the device and one in b<x<2b.

Quantum levitation by LHM?

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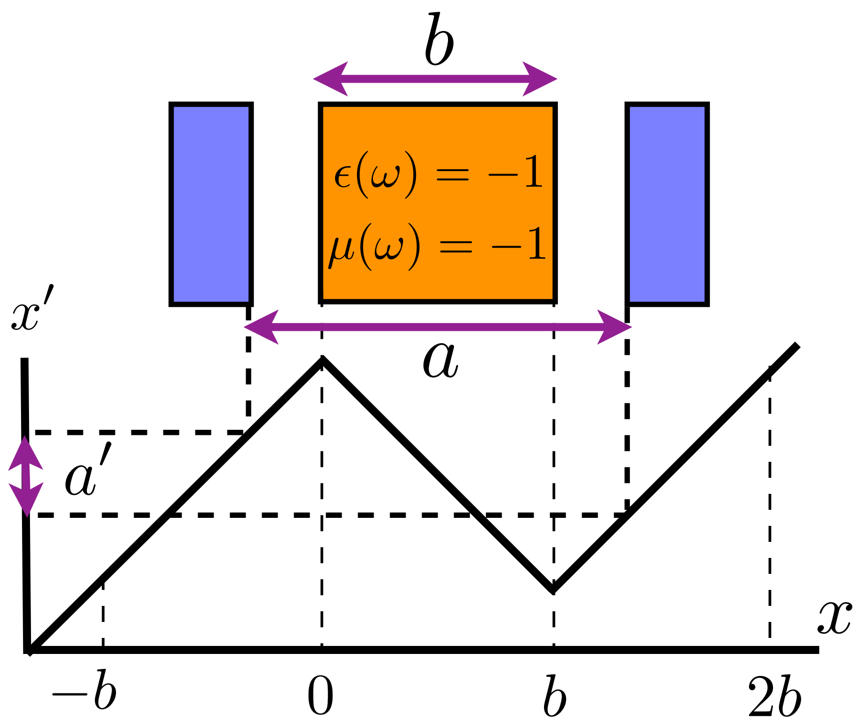
Transformation media

Leonhardt et al, NJP 9, 254 (2007)



Perfect lens: EM field in -b<x<0 is mapped into x'. There are two images, one inside the device and one in b<x<2b.

Casimir cavity: $a' = |a - 2b|$

When a< 2b (plates within the imaging range of the perfect lens)

$$\Rightarrow f = -\frac{\partial U}{\partial a'}\frac{\partial a'}{\partial a} = +\frac{\hbar c \pi^2}{240 a'^4} \Rightarrow \text{Repulsion}$$

Quantum levitation by LHM?

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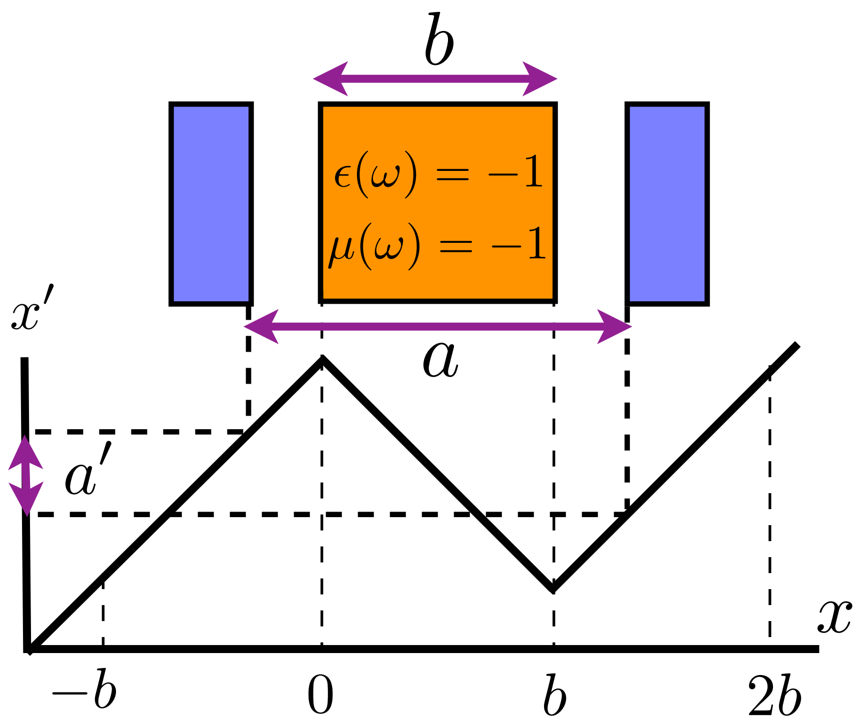
Transformation media   Leonhardt et al, NJP 9, 254 (2007)



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$$\Rightarrow f = -\frac{\partial U}{\partial a'}\frac{\partial a'}{\partial a} = +\frac{\hbar c \pi^2}{240 a'^4} \Rightarrow$$ **Repulsion**

For real materials, however .....

- According to causality, no passive medium ($\epsilon''(\omega) > 0$) can sustain $\epsilon, \mu \simeq -1$ over a wide range of frequencies. In fact, $\epsilon(i\xi), \mu(i\xi) > 0$
- Leonhardt proposes to use an active MM ($\epsilon''(\omega) < 0$) in order to get repulsion. But then the whole approach breaks down, as real photons would be emitted into the quantum vacuum.

Metamaterials for Casimir

Drude-Lorentz model:

$$\epsilon_\alpha(\omega) = 1 - \frac{\Omega^2_{E,\alpha}}{\omega^2 - \omega^2_{E,\alpha} + i\Gamma_{E,\alpha}\omega}$$

$$\mu_\alpha(\omega) = 1 - \frac{\Omega^2_{M,\alpha}}{\omega^2 - \omega^2_{M,\alpha} + i\Gamma_{M,\alpha}\omega}$$

Typical separations

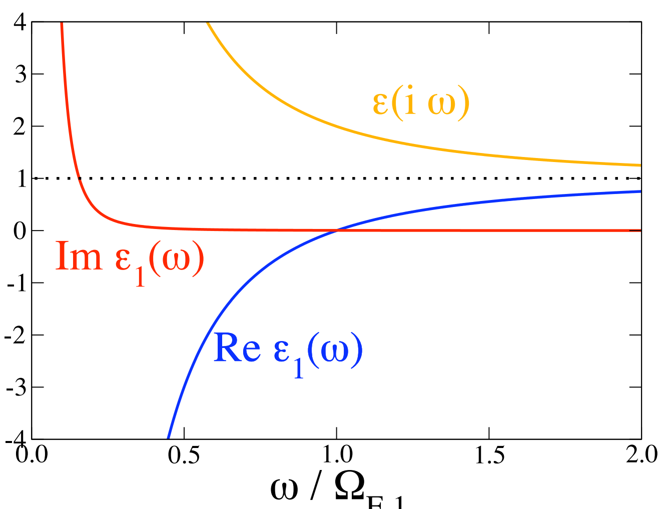
$$d = 200 - 1000 \text{ nm}$$

Infrared-optical frequencies

$$\Omega/2\pi = 5 \times 10^{14} \text{ rad s}^{-1}$$

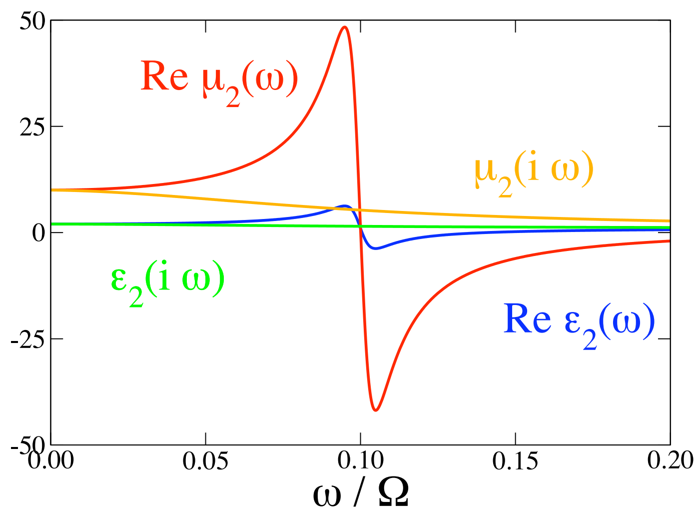
Drude metal (Au)

$\Omega_E = 9.0$ eV $\quad \Gamma_E = 35$ meV



Metamaterial

Re $\epsilon_2(\omega) < 0 \quad$ Re $\mu_2(\omega) < 0$



$$\Omega_{E,2}/\Omega = 0.1 \quad \Omega_{M,2}/\Omega = 0.3$$

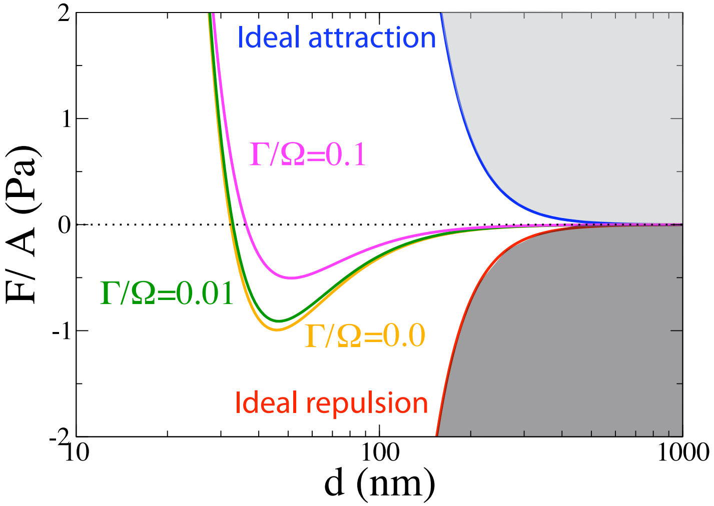
$$\omega_{E,2}/\Omega = \omega_{M,2}/\Omega = 0.1$$

$$\Gamma_{E,2}/\Omega = \Gamma_{M,2}/\Omega = 0.01$$

Metamaterials for Casimir

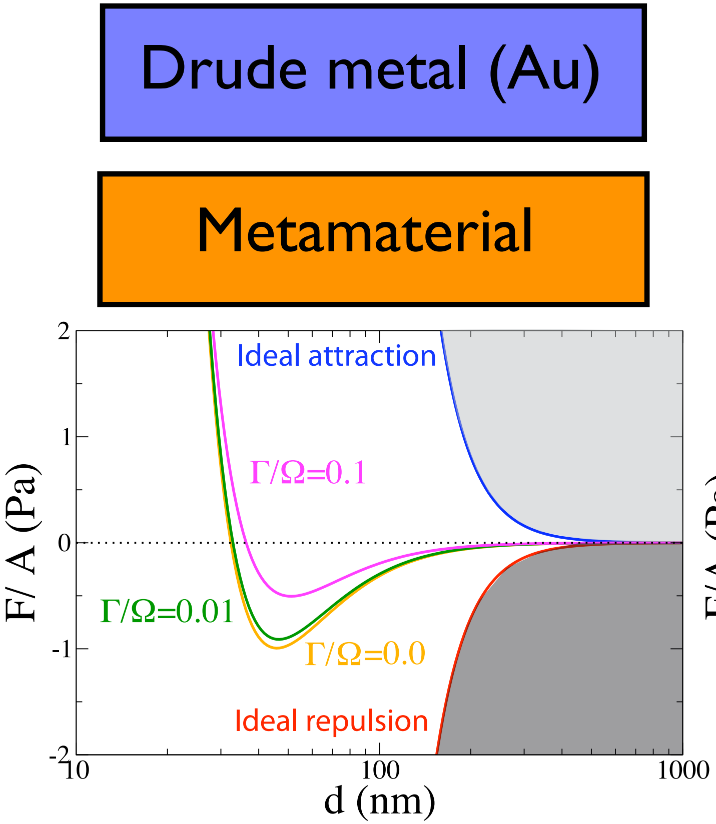
Drude metal (Au)

Metamaterial

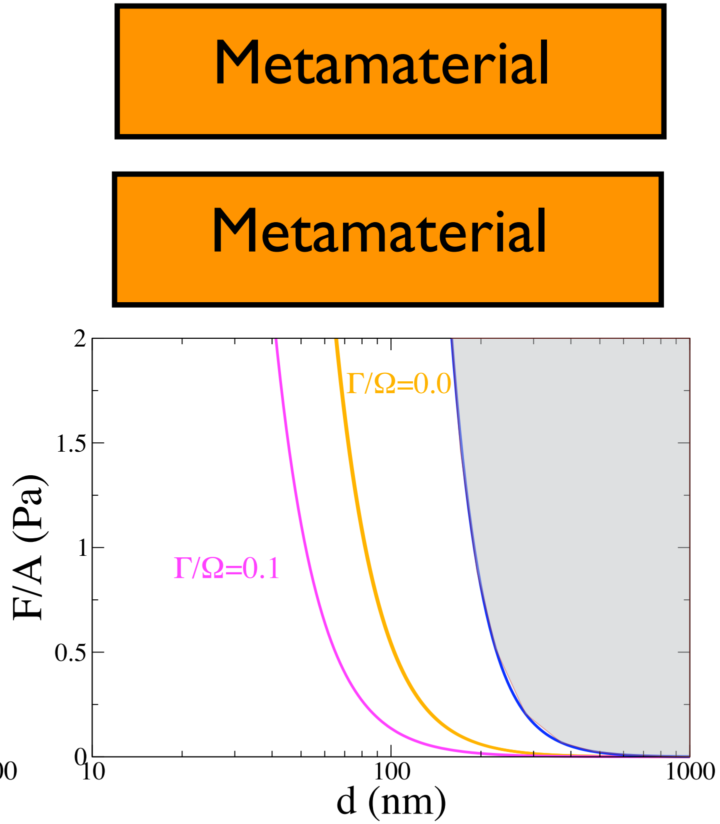


Repulsion-attraction

Metamaterials for Casimir



Repulsion-attraction



Only attraction

Metamaterials for Casimir

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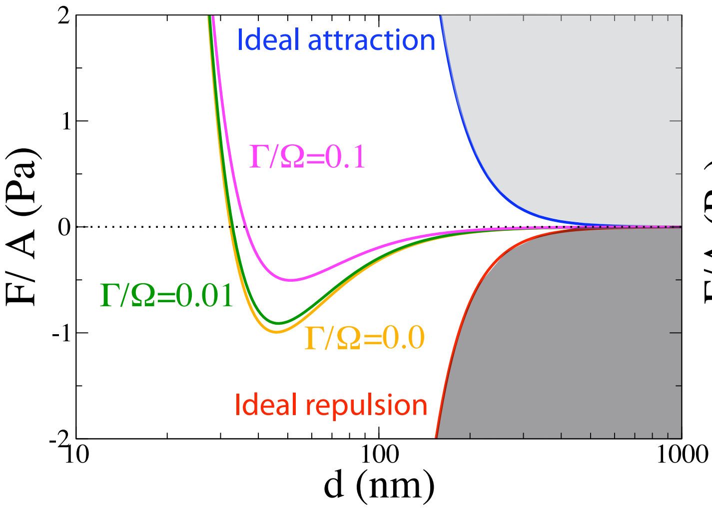
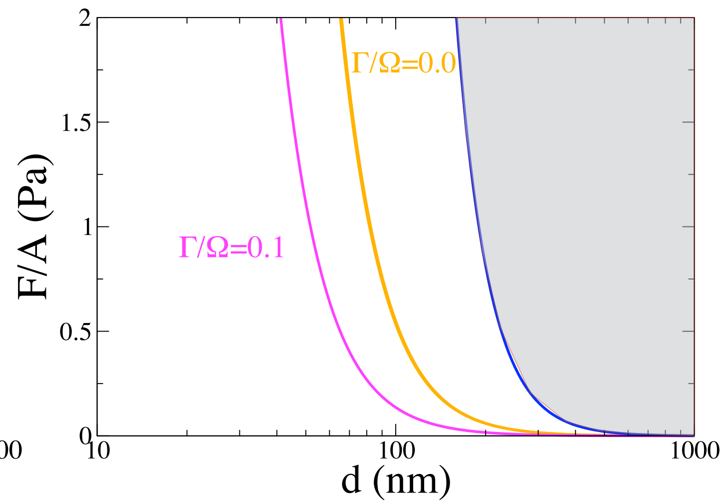
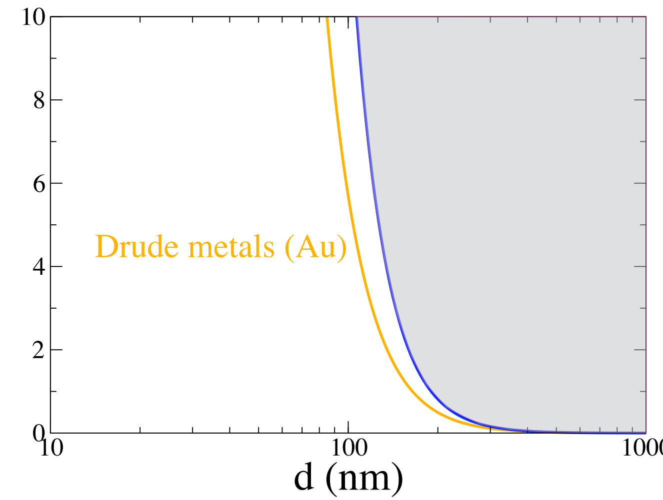
Drude metal (Au)	Metamaterial	Drude metal (Au)
Metamaterial	Metamaterial	Drude metal (Au)



Repulsion-attraction



Only attraction



Only attraction

Metamaterials for Casimir

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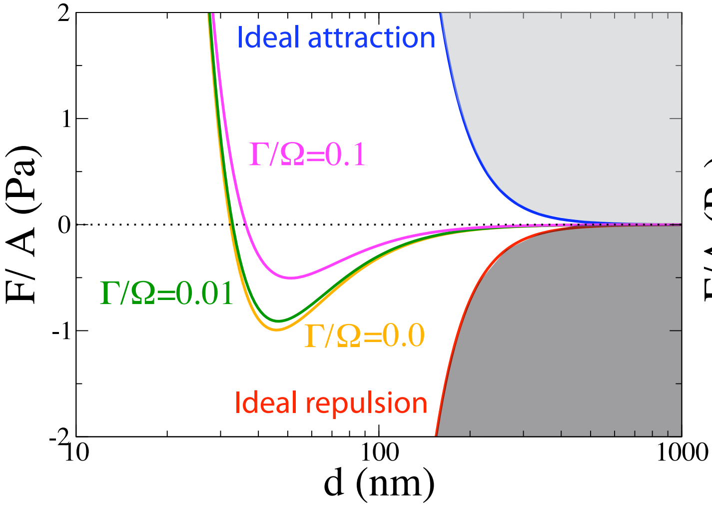
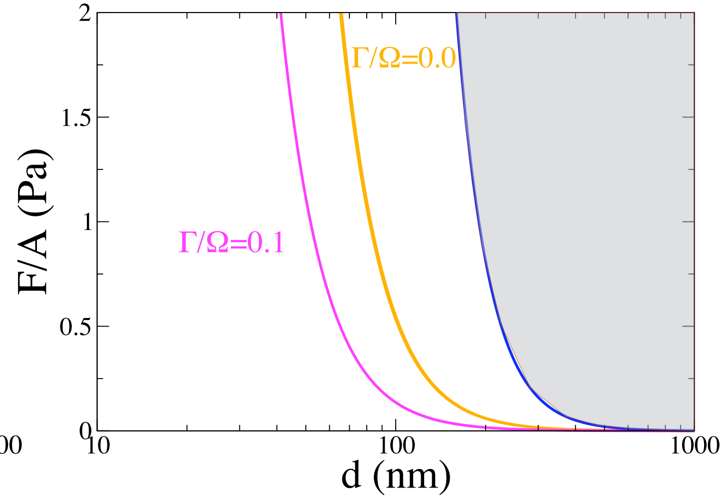
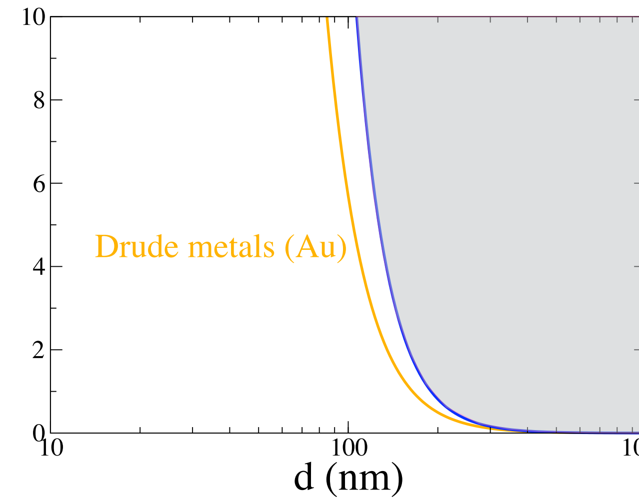
Drude metal (Au)	Metamaterial	Drude metal (Au)
Metamaterial	Metamaterial	Drude metal (Au)



Repulsion-attraction



Only attraction



Only attraction

A slab made of Au ($\rho = 19.3\ \mathrm{gr/cm^3}$) of width $\delta = 1\mu\mathrm{m}$ could levitate in front of one of these MMs at a distance of $d \approx 110\ \mathrm{nm}$!!!

Casimir and metamaterials Henkel et al, EPL 72, 929 (2005)
Casimir and surface plasmons Lambrecht et al, PRL 94, 110404 (2005)
van der Waals in magneto-dielectrics Dalvit et al, PRA 75, 052117 (2007)

Conclusions

- Metamaterials can strongly influence the quantum vacuum, providing a route towards quantum levitation.
- Build MMs with strong magnetic response at infrared-optical frequencies, corresponding to gaps between 200 nm and 10 microns.
- Validity of the continuum description? Extensions of Lifshitz formula to periodic structures...
- Fabrication of MMs on torsion pendulum plane or on oscillating MEMS/NEMS
- Similar issues apply to tailored plasmons, e.g. SAA

The Casimir force and MMs

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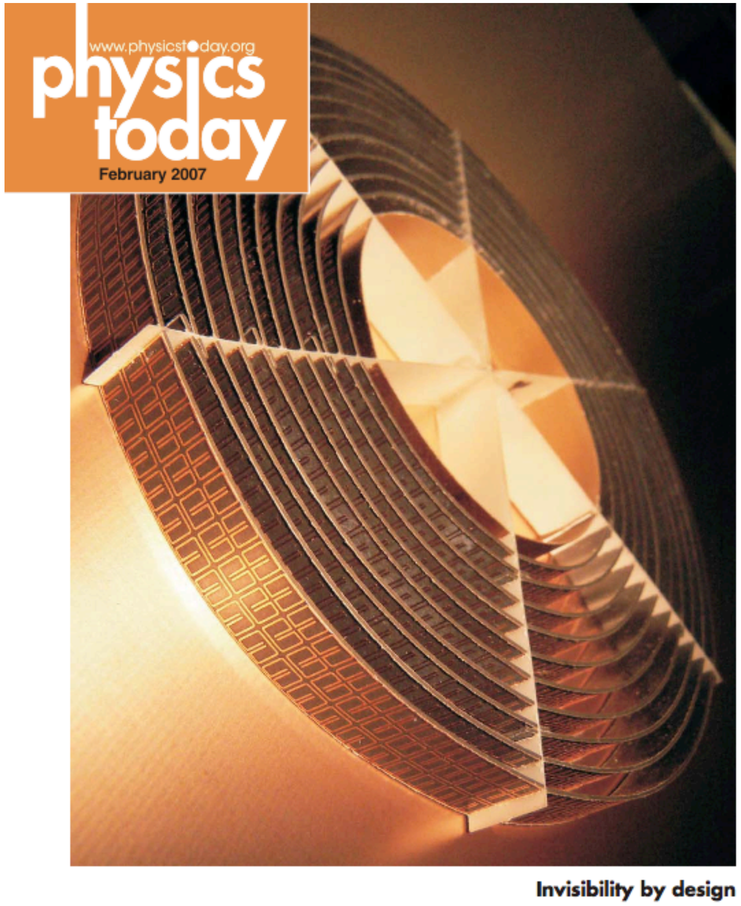

Review article by Steve Lamoreaux on page 40:

“Casimir forces: still surprising after 60 years”